

Geological carbon capture & storage in mafic and ultramafic rocks
IODP/ICDP Workshop on the role of oceanic and continental scientific drilling
Sultan Qaboos University, Muscat, Sultanate of Oman
8-10 January, 2011 with optional field trips on January 11 & 12

1) Summary (up to 1 page)

Mitigation, avoidance and reduction of increasing atmospheric CO₂ concentrations due to burning of hydrocarbons are among the most pressing technological challenges to society. Geological carbon storage is a key component of mitigation strategies. A workshop, recently organized in Muscat (Sultanate of Oman), brought together scientists from communities associated with the Integrated Ocean Drilling Program (IODP) and the International Continental Scientific Drilling Program (ICDP) with colleagues from the geothermal, chemical, and mining industries to raise the profile of research on geological carbon capture and storage, with particular focus on the potential for storage in ultramafic and mafic rocks. The interest in these rocks, little exploited yet for industrial purposes, stems from their high potential for mineral carbonation, which represents one of the safest and most effective means to achieve long term carbon storage.

The workshop was attended by 87 registered participants from 15 countries: Australia, Canada, China (PRC), France, Germany, The Netherlands, Hungary, Iceland, Italy, Japan, Norway, Oman, Switzerland, the UK and the US. The workshop was sponsored by IODP-MI, Sultan Qaboos University, the (US) National Science Foundation, the European Science Foundation, UK-IODP, InterRidge and the (US) Consortium for Ocean Leadership. Convenors were M. Godard (CNRS/UM2, France), P. Kelemen (LDEO, USA), S. Nasir (SQU, Oman) and D. Teagle (NOCS, UK). The Steering Committee also included A. Al Rajhi (OGS, Oman), W. Bach (MARUM, Germany), K. Becker (RSMAS, USA), A. Bonneville (PNL, USA), G. Dipple (UBC, Canada), G. Früh-Green (ETHZ, CH), S. Gíslason (UI, Iceland), D. Goldberg (LDEO, USA), Ph. Gouze (CNRS/UM2, France), M. Hesse (UT, USA), B. Ildefonse (CNRS/UM2, France), J. Matter (LDEO, USA), Ph. Pézard (CNRS/UM2, France), K. Suyehiro (IODP, Japan).

The opening ceremony was attended by Her Royal Highness, Mona Al Saaid and His Excellency Dr. Ali Al Bemani, Vice Chancellor of Sultan Qaboos University. Addresses were given by Dr. Saif Al-Bahri, Dean of the College of Science, and Prof. Peter Kelemen, Chairman of the Workshop. The first plenary lecture was by Prof. Richard Darton of Oxford University, on chemical separation of CO₂.

The workshop was organized as a series of presentations alternating with breakout sessions for discussion. Keynote lectures were on natural and enhanced geological storage of CO₂ in mafic and ultramafic rock formations, experimentally determined rates of CO₂ reaction with rocks, processes in which volume expansion due to formation of carbonate minerals lead to fracture, maintaining or enhancing permeability and reactive surface area, experience with monitoring permeability and CO₂ storage at sea and on land, use of ultramafic mine tailings for mineral carbonation for CO₂ storage, ongoing projects involving CO₂ injection into mafic rocks, and methods for engineered hydraulic fracture – enhancing permeability – in the geothermal power and mining industries. Small working groups met to discuss mineral carbonation on land and at sea, monitoring of CO₂ storage sites, geophysical rock properties necessary for CO₂ storage, ideal storage site characteristics on land and beneath the seafloor, and the role that could be played by ICDP and IODP in this new field of research. The workshop was followed by two days of field trips to view natural mineral carbonation processes in the Oman Mountains.

Consensus was reached over the need to develop integrated international research networks to favor the development of new geological storage techniques adapted for long-term CO₂ storage in mafic and ultramafic reservoirs. Discussions outlined the scientific and technical objectives that could be integrated in the new science plans for international ocean and continental drilling programs as part of these collaborative efforts. Finally, a group of participants have submitted a proposal for an ICDP sponsored workshop to develop a full proposal for scientific drilling in the Samail ophiolite in Oman. One of the objectives of drilling is to investigate present day alteration processes, their relationship to the deep biosphere, and their potential for acceleration to achieve carbon capture and storage via *in situ* mineral carbonation.

2) Description of the scientific content of and discussion at the event (up to 4 pages)

Mitigation, avoidance and possible reduction of increasing atmospheric CO₂ concentrations due to burning of hydrocarbons are among the most pressing technological challenges to our modern society. Geological carbon storage is a key component of many mitigation strategies. *In situ* mineral carbonation may be the safest and most effective means to achieve this. In addition to storage, enhancing geological carbon capture via fluid/rock reactions that remove carbon from air or surface waters may provide an alternative to industrial CO₂ capture and transport, and a route to achieve “negative emissions” should atmospheric CO₂ concentrations become unacceptably high in the future.

Mafic rocks (basalts...) are the most abundant igneous rocks at the Earth’s surface, while ultramafic rocks (mainly peridotites...) have the largest mineral carbonation capacity and fastest known carbonation kinetics amongst the major rock lithologies at Earth’s surface. Observations of active and ancient hydrothermal systems demonstrate rapid and abundant formation of carbonate minerals via reaction of fluids with these rocks. Yet, the potential for storage in mafic and ultramafic rocks is much less well understood compared to storage in pore space in sedimentary rocks, largely because sedimentary rocks form source and reservoir formations for large hydrocarbon resources, whereas mafic and ultramafic rocks do not. Therefore, in contrast to the many ongoing large pilot studies of CO₂ storage into pore space in sedimentary basins, the high carbonation potential of these lithologies rich in divalent cations (Mg, Fe, Ca...) has received relatively little attention yet. The aim of the workshop recently organized in Muscat (Sultanate of Oman) was to raise the profile of research on geological carbon capture and storage in ultramafic and mafic rocks.

Topics addressed during the workshop

The first three days of the workshop were dedicated to presentations and breakout sessions for discussion. Keynote speakers were invited to introduce the themes and open questions, and multidisciplinary discussions took place in guided breakout sessions as well as during the poster session. An important goal of the workshop was to create synergies between scientists working in CCS research and on natural analogues. Therefore, after the workshop, two optional, one day field trips were organized to build a common basis of knowledge and to favor discussion between these different scientific communities, part of which have little to no knowledge of the geology of the ultramafic and mafic reservoirs targeted for CCS studies. On Day 1, we explored the unique outcrops, exposed in the Oman Mountains, illustrating the processes of forming solid minerals containing CO₂, including the white travertine deposits associated with the “blue pools”; Day 2 aimed at offering a broad overview of the geology of the Oman ophiolite, from ultramafic outcrops to the mafic igneous crust. During these five days, several topics were addressed during the discussions:

* *Characterization of the reactivity of the mafic and ultramafic rocks in presence of CO₂-rich fluids (gas, supercritical CO₂, CO₂-saturated water or brine...).* CO₂-rich fluids are in chemical disequilibrium with the ultramafic and mafic rocks. Injection will induce reactive processes at the fluid-rock interface, such as dissolution of mantle silicates (olivine ...) and precipitation of carbonates (carbonation...); the parameters controlling these reactions (e.g., temperature, fluid pressure, kinetics ...) can be studied in the laboratories but also in natural environments.

* *Volume changes during hydration and carbonation processes and feedback effects on the mechanical and hydraulic properties of the media.* The relationship between reaction driven volume changes and permeability is essentially unknown during mineral carbonation. It is intuitive that reactions increasing the solid volume may be self-limiting because they fill pore space and armor reactive surfaces. However, based in part on geological evidence for 100% carbonation of some rocks, it is inferred that mineral carbonation may enter a “reaction-driven cracking regime” in which permeability and reactive surface area are maintained or even enhanced in a positive feedback process. It is absolutely essential to understand the mechanisms controlling these processes.

* *Characterization of the rock hydrodynamic properties before, during and after injection.* The simplest physical and hydrodynamic properties, such as permeability, porosity and their variation with formation age and depth

below the surface, are not well known for our target lithologies. Workshop participants discussed methods for achieving a better characterization of the physical properties of basalt and peridotite formations in natural systems and, what is the research needed to implement these data in the frame of CCS projects.

**CO₂ injection into the mafic and ultramafic rocks.* Injection of CO₂ into pore space in basalts is one technique currently under development. This is underway in the Columbia River flood basalts as part of the DOE-affiliated and funded [Wallula Basalt Sequestration Pilot Project](#) (Big Sky Partnership, DOE, USA). Another pilot project in Iceland, [CarbFix](#), should begin injection of CO₂ into basalts in Iceland in 2011. These studies are of great interest because of the potentially enormous volumes of high porosity basalt overlain by sedimentary cap rocks in both offshore and onshore environments. Also, these techniques “split the difference” between (a) more or less conventional CO₂ injection into pore space, which has been applied to enhanced oil recovery for decades, and (b) new ideas about *in situ* mineral carbonation for CO₂ storage. On the other hand, effective, enhanced mineral carbonation in low porosity/permeability ultramafic systems will almost certainly require “hydraulic stimulation” of rock formations at depth. Hydraulic fracture has long been employed to enhance the flow of oil from reservoir rocks, and is being intensively developed more systematically for extraction of gas from “tight” shale reservoirs with very low permeability. These different techniques were discussed by workshop participants. They benefited from a good participation from Big Sky and CarbFix participants in the workshop, as some of the principal scientists involved are members of our Steering Committee.

* *Environmental and safety issues.* Environmental concerns about CO₂ storage abound: (a) displacement of saline water from subsurface pore space, with potential for migration of saline fluids into potable water supplies, (b) similar issues involving migration of fluids (mainly water but with a few percent additives whose exact nature is often proprietary) used in hydraulic stimulation or with metals present in dissolved peridotites and basalts (Ni, Cr, As, Pb...) into drinking water or the surface environment, (c) the potential for increased earthquake activity due to fault “lubrication” by injected fluids and to elevated fluid pressure reducing the resistance of rocks to the formation of new fractures, and (d) the potential for significant surface deformation associated with volume expansion at depth. These issues and possible solutions were addressed during the workshop by the different working groups.

Scientific challenges and new paths for research

One of the first outcomes of the interdisciplinary discussions during the workshop was to challenge the idea that ultramafic and mafic formations could not provide significantly large storage capacities for CO₂ and would eventually represent only accessory target sites in geographic areas where classical sedimentary reservoirs are not available (e.g., Iceland). First, when available, observations of the sub-seafloor systems indicates that water (and therefore CO₂) infiltrates and alter efficiently peridotites and basalts on short time scales and over significant distances (Kelemen, Teagle, *this workshop*). Second, studies of ultramafic by-products of Cr-Ni mining indicates that natural carbonation due to weathering is a fast process (less than a few years) and that ultramafic mine tailings have the same size and CO₂ storage capacity as the sedimentary reservoirs, such as [Sleipner](#), targeted for pilot studies of CO₂ storage (Dipple, *this workshop*). The differences between the prediction of the storage capacity of (ultra-)mafic rocks for CO₂ sequestration and evidences brought by the observations of natural analogues emphasize the lack of basic knowledge on the transport of fluids in these rock formations and on their reactivity over different time and length scales.

The discussions over the different topics outlined above allowed identifying several scientific questions specific to mafic and ultramafic reservoirs that need to be addressed for the development of CCS in these geological systems. Solving these questions will also allow getting a better understanding of the natural carbon cycle and in particular, to better quantify the role of sub-seafloor hydrothermal alteration and of weathering of peridotites and igneous basaltic crust in this global cycle.

In this context, the first difficulty in identifying research targets and tools to address them is that mafic and ultramafic rocks have significantly different physical, mechanical and hydrodynamic properties, as well as mineralogical and chemical properties. The second difficulty is that the reactivity of these systems and therefore the resulting changes of their properties over time will strongly depend on the nature of the

infiltrated fluid, that is a fluid in high disequilibrium with the rock in the case of a CO₂ injection site (e.g., supercritical CO₂, CO₂ enriched / saturated water or brine) or a fluid close to equilibrium with atmospheric CO₂ in natural hydrothermal systems. It should be noted that natural mineral carbonation is inextricably linked with mineral hydration, occurring mainly in near-surface hydrothermal and weathering environments. Nevertheless, understanding these natural processes provides essential insight for the design of enhanced, *in situ* mineral carbonation systems. To tackle these issues, the participants first identified the scientific questions specific to both mafic and ultramafic reservoirs. Then, they identified means of addressing the scientific and technical problems taking into account the specificity of mafic and ultramafic rock formations: first, with the aim of a better understanding of global carbon balance, second, with the aim of developing new pilot projects for CCS in ultramafic and mafic systems.

The main scientific and technical challenges are:

(i) to characterize the bio-geochemical processes limiting/enhancing transport and carbonation efficiency over a large scale of temperatures and pressures (characteristic of on-land weathering to deep-seated sub-seafloor hydrothermal sites): reaction kinetics and rate-limiting processes (armoring/coating), changes of reactivity and solubility, role of key variables such as climate, substrate materials, catalysis, reactive surface areas ..., biological role in mineral dissolution and precipitation mechanisms;

(ii) to acquire a better knowledge of the hydrogeology of the ultramafic and mafic geological systems, and of the physical mechanisms enhancing/limiting permeability and other hydraulic parameters (injectivity, area of influence, capacity ...) in these systems (e.g., volume changes, natural hydraulic fracturing ...);

And, for application to CO₂ storage,

(iii) to define methods to optimize reactive processes (e.g., with supply of reactants, increasing reactive surface areas) and to improve transport (injectivity, feedbacks) while limiting leaks toward the atmosphere (cap-rock, sub-seafloor storage...);

(iv) to characterize the possible collateral benefits (e.g., resources such as SiO₂, metals (Cu, Zn)) and costs (e.g., release of toxic metals and contaminants such as Al, Cr, Ni, heavy metals and fluoride (from basalts));

(v) to develop methods having the least environmental and societal impact, for example by assessing point solutions (mine sites) vs. distributed solutions (e.g. olivine distribution over soils).

To address these issues, the participants outlined the need for integrative scientific projects involving laboratory experiments, theoretical developments and modeling and also acquisition of new data, both at the surface and deep subsurface. The participants identified topics on which there is active research and technological development in the scientific drilling communities that are highly complementary to our goals and which should be encouraged in the framework of integrated research projects on CO₂ sequestration:

(i) getting a better understanding of alteration and aging of basalts and ultramafic rocks and the contribution of these processes to global carbon budget; the main unknowns are:

* the role of the sub-surface alteration of basaltic flows: getting more data on the hydraulic properties of these systems both at sea and on-land using specifically designed experiments (e.g., Juan de Fuca experiments) and more data on the mineralogic and bio-geochemical evolution of the basaltic oceanic lithosphere during aging (e.g., tracing carbonation processes, the role of changes in pCO₂ in seawater with time) is needed;

* the role of ultramafic oceanic lithosphere: the need for a better understanding of the distribution of seafloor ultramafic rocks (mapping ...) and of the hydrogeology of these rocks (including heat flow, permeability and its age variation) as well as of their mineralogic and bio-geochemical evolution during hydrothermal alteration in both sedimented and unsedimented ridge systems should be included in the oceanic drilling research plans;

(ii) Monitoring, Verification, and Accounting: the specific designs for borehole tools and techniques developed (and still being developed) to study the ultramafic and mafic lithosphere over long periods of time in, sometimes, extreme conditions (e.g., sub-seafloor) during the scientific drilling programs (e.g., CORK pressure monitoring and CORK OsmoSamplers for chemical monitoring ...) will be a major asset to define MVA methods in the framework of CO₂ storage projects in ultramafic and mafic rocks; the expertise in long term management

developed over the years by the scientific drilling program community will also be useful for developing the integrated engineering and scientific network necessary to develop any future CO₂ storage projects.

Finally, consensus was reached for the need to support the development of CO₂ storage pilot projects in mafic and ultramafic rock formations: only test sites will allow evaluating technology for - and in-situ effects of – the different methods envisaged for delivering CO₂ into the different rock formations (e.g., liquid CO₂ or oversaturated seawater). The participants noted that there are no pilot sites in ultramafic rock formations yet, although such site would be an invaluable complement to the two on-going pilot projects in basaltic formation; for instance, it should not be assumed *a priori* that CO₂ sequestration will be more effective in ultramafic rocks than in basalts - rates may be more comparable and permeability in basalts may be more conducive than previously assumed. As a consequence, to develop a CO₂ injection pilot project in ultramafic systems, studies of natural carbonating systems on-land (e.g., Oman alkaline sources) and off-shore (e.g., Lost City, New Caledonia, Rainbow) should come first to gather the general understanding of the thermodynamic and bio-geochemical conditions that have (and will) favor carbonate precipitation and design the experiment (timescales, ...).

As a first step toward future off-shore and on-land pilot studies, the participants defined ideal characteristics for **experimental sites**, where an engineered pilot study can be carried out, and for **study areas**, where information can be gathered to address scientific and technical requirements for the pilot site:

(i) Study areas and experimental sites should be well-surveyed areas (geophysics, hydrogeology, availability of baseline monitoring over years, e.g. to control seasonal variability) where subsurface biosphere can be (is) characterized; multiple holes are necessary to allow cross-hole studies (to allow tracer tests for example);

(ii) Study areas should allow addressing other scientific objectives, e.g. paleo-oceanographic and tectonic objectives for oceanic scientific drilling.

(iii) Experimental sites should be close to CO₂ production sites, have a high permeability to allow injection of large volume of CO₂, have a seal (cap-rock, non conventional seal ...) and also, be scalable to larger studies (if Sleipner is taken as a benchmark, a pilot site should scale at 1 kT injected CO₂ per year, while a real project will be in the order of 1MT per year).

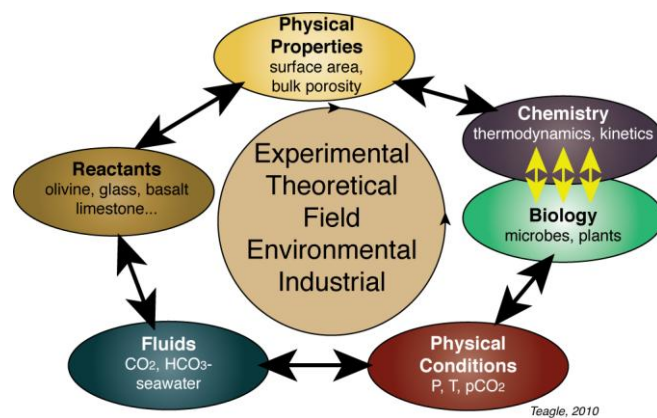
(iv) The sub-surface at experimental sites should preferably be dominantly composed of fresh rocks to favor reactivity (hydrothermal systems should be avoided); nevertheless, the potential for CO₂ storage of sedimented basalts and ultramafic rocks should not be over-sighted.

(v) Concerns over permitting and societal acceptance may be addressed via creation of offshore CO₂ storage reservoirs but then their integrated costs become high if wells are drilled at sea. To limit costs and for practicality, a sub-seafloor pilot site should preferentially be close to land, in deep water if concentrated CO₂ is used (at water depths >2700m, CO₂ is denser than water, and therefore limits need of caprock to prevent leakage toward atmosphere) although shallow water has better logistics (only for aqueous CO₂).

Possible target areas were proposed for experimental and pilot sites. Potential sites abound on-land in basalts and flood basalts. The most favorable ones would allow combining CO₂ sequestration and hydrocarbon research (e.g., China, Norway, Kudu Gas fields, Deccan ...). Komatiites, although they represent only small volumes, can be attractive local solutions (e.g., southern India, South Africa). Proposed off-shore study areas in basalts are Juan de Fuca and the 504B/896 area (drilled and open thus allowing cross hole studies), and for experimental sites, the deep pyroclastic zones adjacent to ocean islands (e.g., Iceland) and flood basalts (close to shore such as the north Atlantic), which allow easy comparison with land. On-land ultramafic sites are mainly peridotite massifs: Oman, North California (Trinity ...), New Caledonia, Ronda, Adriatic, Cyprus, Tuscany (geothermal), North Queensland (Marlborough which is near coal CCS problem). Off shore, several potential study areas in ultramafic basement were suggested: Lost City, New Caledonia, Rainbow, Galicia Margin, and the ultraslow spreading Lena Trough. The proposed potential experimental sites were mostly shoreline ultramafic formations associated with large on-land orogenic peridotite massifs: Oman, New Caledonia, Alboran Sea (Ronda massif), Nicoya Peninsula (Costa Rica).

3) Assessment of the results and impact of the event on the future direction of the field (up to 2 pages)

The development of CO₂ storage in mafic and ultramafic formations is still in its infancy. Only two pilot experiments have been funded yet in basaltic reservoirs compared to more than 20 pilots projects in sedimentary reservoirs, including at least 6 in Europe (Source : [IEAGHG¹](#)); this discrepancy is due mainly to little interest from industry. This lack of interest results in part from the lack of scientific tools to actually predict the fate of CO₂ in these rock formations and therefore to estimate the costs (economic and environmental) and efficiency of this method for mitigating excess of atmospheric CO₂. Nevertheless, the strong potential of these rock formations for *in situ* carbonation, and therefore long term safe CO₂ storage is recognized by the scientific community. In this workshop, we discussed different paths of research to better characterize the physical and chemical processes that will favor (or hinder) CO₂ storage in mafic and ultramafic rocks as well as the technical challenges specific to this goal with a special focus on how the ocean and continental drilling programs can be used to tackle this new scientific challenge.



Flow chart summarizing the research and technological issues for the development of geological storage in (ultra-)mafic rock formations.

The development of new geological storage techniques adapted for long-term CO₂ storage demands both upstream fundamental research on the physical, mineralogy and bio-chemical processes that are (will be) taking place in natural and enhanced hydrothermal systems and a strong interaction with the industry and society, to meet their economic, environmental and societal demands. This program for research and development will need the development of planning structures and/or networks structure for scientists and engineers to work together regularly; workshops, such as the one organized in Oman, are insufficient to create the necessary momentum.

During the workshop, we discussed the possibilities of developing network programs to couple basic fundamental research on enhanced mineral carbonation techniques (such as in mine tailings) with ongoing, complementary studies of hydrothermal alteration and weathering, and of chemosynthetic biological communities in these environments toward applied technologies of CO₂ storage. Several national (e.g., NSF) and international research agencies (e.g., EU funding agencies) could provide the incentive to develop such integrated research networks.

The collaborative efforts of ICDP and IODP will be needed to assess and then overcome the technological challenges involved in the development of carbon storage in ultramafic and mafic reservoirs. In particular, scientific drilling will be an invaluable asset to tackle one of the major challenges for the development of carbon storage that is understanding how to scale lab and modeling studies to *in situ* systems. Discussions outlined the scientific and technical objectives that could be integrated in the future scientific objectives for international ocean and continental drilling programs (detailed above).

¹ International Energy Agency Greenhouse Gas R&D Programme

Geological carbon capture & storage and, more extensively, global carbon fluxes are topics of interest also for other scientific initiatives, such as the Deep Carbon Observatory ([DCO](#)). The DCO is a recent multidisciplinary and international initiative dedicated to the study of Earth's deep carbon cycles. One of its research themes is the study of deep carbon reservoirs to inform CO₂ storage in deep reservoirs (Energy, Environment and Climate Working Group). Also, a workshop “Reaching the Mantle Frontier: Moho and Beyond” was recently organized during which the possible synergies between the scientific targets of DCO and IODP were outlined.

Finally, as a first step toward more integrated research on mafic and ultramafic reservoirs, an international group of scientists have submitted a proposal for an ICDP sponsored workshop to develop a full proposal for scientific drilling in the Samail ophiolite in Oman. The Samail ophiolite is composed of igneous crust and upper mantle formed at a submarine spreading center, via processes very similar to those at mid-ocean ridges today. Drilling will provide key data on the hydrothermal modification of that crust. Drilling will also investigate present day alteration processes, their relationship to the deep biosphere, and their potential for acceleration to achieve carbon capture and storage via *in situ* mineral carbonation. This proposal, led by Peter Kelemen, has 22 formal proponents, including Dr. Ali Al Rajhi, Director of the Geological Survey of Oman and Associate Director General of Minerals in the Ministry of Commerce and Industry, and Prof. Sobhi Nasir, Head, Geology Department, Sultan Qaboos University. The proponents and a larger group of co-proponents include scientists from Australia, Canada, France, Germany, Italy, Japan, Oman, Switzerland, the UK and the US. It is anticipated that participation by representatives of the Omani Ministry of the Environment and Ministry of Water Resources will be essential to design an effective strategy for scientific drilling in Oman.

4) Final programme of the meeting

The 3-day workshop was organized as a series of invited talks and discussions in working groups as well as during poster sessions. Session coordinators provided short reviews of each day discussions.

Invited talks were organized as:

- Keynote presentations: 30 min talk and followed by 10 min questions & discussion
- Coordinated presentations of fundamentals scientific and technical issues: 20 min talks followed by 10 min questions & discussion

• Friday January 7, 2011

19:00-22:00 Registration & Icebreaker at Sultan Qaboos University
(Faculty Club Restaurant near Administration building)

• Saturday January 8, 2011

08:00-09:00 Further Registration "On Site" - Sultan Qaboos University

09:00-10:20 Opening ceremony

09:05 Recitation from the Holy Quran

09:10 Address by Dr. Saif Al-Bahri – Dean, College of Science

09:20 Address by Prof. Peter Kelemen - Chairman of the Conference

09:30-10:10 CO₂ emissions: Capture them or avoid them, it's a big challenge - *R. Darton - Univ of Oxford, UK*

Summary: The world economy runs on the consumption of a large and increasing flow of fossil carbon fuel, which is currently generating some 30 billion tpy of carbon dioxide. Whether we plan to sequester this flow (CCS), or avoid it (low-Carbon economy) the challenge is a huge one. We have to consider both the scale of the engineering, and the scale of societal change. We also have to consider the role that could be played a number of different technologies, since it seems unlikely that there will be a single preferred path of change.

10:10-10:20 Closing Ceremony

10:20-10:50 Coffee break

10:50-11:30 Potential for in situ geological storage in mafic rocks: Fundamental mechanisms and lessons from field observation – *D. Teagle – NOCS, UK.*

11:30-12:10 Potential for in situ geological storage in ultramafic rocks: Fundamental mechanisms and lessons from field observation – *P. Kelemen – LDEO, USA.*

12:15-13:45 Lunch

13:45-14:15 Fundamental mechanisms of CO₂ mineral storage: lessons from laboratory experiments- *E. Oelkers – Univ. Toulouse, France.*

14:15 - 14:45 Feedbacks between reactions and hydrodynamic properties of reacting media: lessons from experiments - *Ph Gouze – Univ. Montpellier, France.*

14:45 - 15:15 Physical feedbacks during mineral carbonation: field observations, experiments and models - *B. Jamtveit – Univ. Oslo, Norway.*

15:15-15:45 Coffee break

15:45-16:15 Hydrogeology: Field observation & lessons from IODP - *K. Becker - RSMAS, USA.*

16:15-16:45 Monitoring and verification of CO₂ storage - *J. Matter – LDEO, USA.*

16:45-17:15 Summary of day

17:15-19:30 Discussions around Posters (Refreshments available)

19:30-20:30 Dinner

• **Sunday January 9, 2011**

08:30-09:00 Coffee on Site

09:00-09:40 Enhanced weathering and carbon mineralization in mine waste: acceleration potential and implications for carbon sequestration – *G. Dipple- UBC, Canada.*

09:40-10:00 Organize people into breakout sessions.

10:00-10:40 Working Groups I: Theme and coordinators

WG1 - Natural systems & in situ storage in the seafloor (processes and IODP targets):

K. Becker/G. Früh-Green

WG2 - Natural systems & in situ storage on land (ICDP targets): T. McLing/S. Mackintosh

WG3 - Enhanced weathering options - mine tailings/industrial waste: D. Teagle/J. West

WG4 – Kinetics, fluid flow, reaction, efficiencies: V. Prigiobbe / K. Evans

10:40-11:10 Coffee available

11:10-12:30 Working Groups I (continues)

12:30-14:00 Lunch

14:00-15:00 Ongoing projects:

- CarbFix - *S. Gislason -U. of Iceland.*

- Big Sky- *P. McGrail – PNNL, USA.*

15:00-16:00 Summaries of Working Group Discussions

16:00-16:30 Coffee break

16:30-17:10 Technical challenges, lessons from engineered geothermal system for CCS - *Roy Baria – EGS Energy Ltd, UK.*

17:10-18:00 Summaries of Working Group Discussions (Part 2) & Actions for Day 3 (reminder of WGII program)

18:00-19:30 Discussions around Posters (Refreshments available)

19:30-20:30 Dinner

• **Monday January 10, 2011**

08:30-09:00 Coffee on Site

09:00-09:40 Creating surface area and conductivity in ultramafic rocks by using extremely closely spaced hydraulic fractures- *A. Bunger – CSIRO, Australia.*

09:40-10:00 Organize people into breakout sessions (Working Groups II)...

10:00-10:40 Working Groups II: Theme and coordinators

WG1 - submarine site characteristics: M. Godard & P. Michael

WG2 - onland site characteristics: G. Pearson & M. Oristaglio

WG3 - permeability, hydraulic fracture, reactive surface area: G. Dipple & A. Bunger

10:40-11:10 Coffee available

11:10-12:30 Working Groups II (continues)

12:30-14:00 Lunch

14:00-14:30 A last look at the Posters

14:30-16:00 Summary of Working Group II Discussions

16:00-16:30 Coffee break

16:30-18:00 Summary of Working Group Discussions

18:00-19:00 Close Formal Meeting

19:30-20:30 Dinner

5) Appendix to the report:

Budget:

The cost of the workshop was more than initially expected: we planned the workshop for 50-60 participants and there were 87 participants. The **total estimated expenditure** (including an estimate of the travel costs not covered by our sponsors) is **121000 euros**.

List of sponsors

European Science Foundation – Magellan Workshop Series: 16500 €
 Ocean Leadership (*travel grants - only for U.S. based scientists*): 44000 US \$
 U.S. National Science Foundation (*travel grants - only for U.S. based scientists*): 29000 US \$
 U.K IODP (*travel grants - only for U.K. based scientists*): 5000 GBP
 InterRidge (*travel grants*): 5000 US \$
Total: 85150 euros

List of participants: 87 participants (*including 10 PhD students and 11 post-docs and young scientists*). 32 participants were European (Iceland not included) and 13 from the Sultanate of Oman. The names of the participants which expenses were covered in part or completely by the Magellan ESF grant are in bold characters.

Muriel Andreani	**	ENS-Université de Lyon, France	muriel.andreani@univ-lyon1.fr
Caitlin Augustin	*	School of Marine and Atmospheric Science University of Miami, USA	c.augustin@umiami.edu
Hafidh Khlafan Al Ghanami		Ministry of Commerce, Sultanate of Oman	-
Abdulrahman Al Harthi		Department of Earth Science, Sultan Qaboos University, Sultanate of Oman	-
Mohamed Issa Al Harthi		Ministry of Commerce, Sultanate of Oman	-
Talal Al Hosni		Sultan Qaboos University, Sultanate of Oman	hosni@squ.edu.om
Zhair Al Suleimani		Public Authority for Electricity and Water, Sultanate of Oman	-
Saleh Al-Anboori		Ministry of Oil & Gas, Sultanate of Oman	-
Abdelmajeed Abdullah Al-Ansari		Ministry of Commerce, Sultanate of Oman	-
Yahya Al-Wahaibi		Sultan Qaboos University, Sultanate of Oman	ymn@squ.edu.om
Ibrahim Ashour		Department of Petroleum and Chemical Engineering, Sultan Qaboos University, Sultanate of Oman	ashour@squ.edu.om
Roy Baria		MIL-TECH UK Ltd	roybaria@onetel.com
Keir Becker		University of Miami - RSMAS, USA	kbecker@rsmas.miami.edu
Claire Bendersky	*	Lamont Doherty Earth Observatory, USA	claireb@ldeo.columbia.edu
Pascale Benezeth		Laboratoire des Mécanismes et Transferts en Géologie (LMTG-CNRS)- Toulouse, France	benezeth@lmtg.obs-mip.fr
Dominique Bernard		ICMCB-CNRS, France	bernard@icmcb-bordeaux.cnrs.fr
Eleanor Berryman	*	McGill University, Canada	eleanor.berryman@mail.mcgill.ca
Márton Berta	*	ELTE University, Budapest, Hungary	marci87@chello.hu
Chiara Boschi		Institute of Geosciences and Earth Resources-CNR, Italy	c.boschi@igg.cnr.it
Françoise Boudier		Université Montpellier 2, France	Francoise.Boudier@gm.univ-montp2.fr
Andrew Bungler		CSIRO Earth Science and Resource Engineering, Australia	andrew.bunger@csiro.au
Richard Darton		University of Oxford, UK	richard.darton@eng.ox.ac.uk
Henri Dick		Woods Hole Oceanographic Institution, USA	hdick@whoi.edu

Andrea Dini		Institute of Geosciences and Earth Resources-CNR, Italy	a.dini@igg.cnr.it
Gregory M. Dipple		University of British Columbia, Canada	gdipple@eos.ubc.ca
Steve Ehreinberg		Shell Chair, Sultan Qaboos University, Sultanate of Oman	sne@squ.edu.om
Issa El-Hussain		Sultan Qaboos University, Sultanate of Oman	elhussain@squ.edu.om
Katy Evans		Curtin University, Australia	k.evans@curtin.edu.au
Gretchen Früh-Green		ETH Zurich, Switzerland	frueh-green@erdw.ethz.ch
Eric Gaidos		Department of Geology and Geophysics, University of Hawaii, USA	gaidos@hawaii.edu
Pablo Garcia Del Real	*	Stanford University, USA	gdelreal@stanford.edu
Sigurdur Gislason		Institute of Earth Sciences, University of Iceland	sigrg@raunvis.hi.is
Marguerite Godard		CNRS-Géosciences Montpellier, France	Marguerite.Godard@um2.fr
David S. Goldberg		Lamont-Doherty Earth Observatory, USA	goldberg@ldeo.columbia.edu
Philippe Gouze		CNRS-Géosciences Montpellier, France	Philippe.Gouze@um2.fr
Marc Hesse	**	University of Texas at Austin, USA	mhesse@jsg.utexas.edu
Astrid Holzheid		Universität Kiel, Germany	holzheid@min.uni-kiel.de
Richard Hunwick		Integrated Carbon Sequestration Pty Ltd (ICS), Australia	richard@hunwickconsultants.com.au
Benoît Ildefonse		CNRS - Géosciences Montpellier, France	benoit.ildefonse@um2.fr
Karthik Iyer	**	The Future Ocean, IfM-GEOMAR, Germany	kiyer@ifm-geomar.de
Bjorn Jamveit		PGP, University of Oslo, Norway	bjorn.jamtveit@geo.uio.no
Junfeng Ji		School of Earth Sciences and Engineering, Nanjing University, P. R. China	jijunfeng@nju.edu.cn
Kevin Johnson		University of Hawaii, USA	kjohnso2@hawaii.edu
Natalie Johnson	*	Stanford University, USA	nataliej@stanford.edu
Jens Kallmeyer		University of Potsdam, Institute of Earth and Environmental Sciences, Germany	kallm@geo.uni-potsdam.de
Peter Kelemen		Columbia University, USA	peterk@LDEO.columbia.edu
Juergen Koepke		Leibniz University Hannover, Germany	koepke@mineralogie.uni-hannover.de
Marvin Lilley		School of Oceanography, University of Washington, USA	lilley@u.washington.edu
Harrison Lisabeth	**	Columbia University, USA	hlisabeth@gmail.com
Kristin Ludwig		Consortium for Ocean Leadership, USA	kludwig@oceanleadership.org
Sarah Mackintosh	**	The University of Nottingham, UK	Sarah.Mackintosh@nottingham.ac.uk
Jagan Mahadevan	**	The University of Tulsa, USA	jmahadevan@utulsa.edu
David Manning		University of Newcastle, UK	David.Manning@newcastle.ac.uk
Juerg Matter		Lamont-Doherty Earth Observatory of Columbia University, USA	jmatter@ldeo.columbia.edu
B. Peter McGrail		Pacific Northwest National Laboratory, USA	pete.mcgrail@pnl.gov
Travis L. McLing		Idaho National Laboratory, Center for Advanced Energy Studies, USA	travis.mcling@inl.gov
Bénédicte Menez		CNRS - Institut de Physique du Globe de Paris, France	menez@ipgp.fr
Peter Michael		The University of Tulsa, USA	pjm@utulsa.edu
Katsuyoshi Michibayashi		Shizuoka University, Japan	sekmich@ipc.shizuoka.ac.jp

Jay Miller		Integrated Ocean Drilling Program	miller@iodp.tamu.edu
Christophe Monnin		CNRS- Université Paul Sabatier, France	monnin@lmtg.obs-mip.fr
Sobhi Nasir		Sultan Qaboos University, Sultanate of Oman	sobhi@squ.edu.om
Eric Oelkers		CNRS- Université Paul Sabatier, France	oelkers@lmtg.obs-mip.fr
Jonas Olsson	*	Nordic Volcanological Institute, Institute of Earth Sciences, University of Iceland	jolsson@hi.is
Mike Oristaglio		Yale University, USA	michael.oristaglio@yale.edu
Jason Ornstein	*	New York University, USA	jmo326@nyu.edu
Amelia Paukert	*	Columbia University, USA	anp2119@columbia.edu
D. Graham Pearson		University of Alberta, Canada	gdpearso@ualberta.ca
Robert Podgorney		Idaho National Laboratory and Center for Advanced Energy Studies, USA	robert.podgorney@inl.gov
Herbert Poellmann		University of Halle, Germany	herbert.poellmann@geo.uni-halle.de
Bernhard Pracejus		Sultan Qaboos University, Sultanate of Oman	pracejus@squ.edu.om
Valentina Prigobbe	**	University of Texas at Austin, USA	valentina.prigobbe@mail.utexas.edu
Barbara Ransom		National Science Foundation, USA	bransom@nsf.gov
Lars Ruepke		The Future Ocean - IFM-GEOMAR; Germany	lruepke@ifm-geomar.de
Olaf Schuiling		Institute of Geosciences, Utrecht University, The Netherlands	schuiling@geo.uu.nl
Nina S.C. Simon	**	Environmental technology, Norway	nina.simon@ife.no
Sven Sindern		RWTH Aachen University, Germany	sindern@rwth-aachen.de
Michael Styles		British Geological Survey, UK	mts@bgs.ac.uk
Narasimman Sundararajan		Sultan Qaboos University, Sultanate of Oman	visvid12@squ.edu.om
Yutaro Takaya	*	Department of Systems Innovation, Graduate School of Engineering, University of Tokyo, Japan	tt097074@mail.ecc.u-tokyo.ac.jp
Damon Teagle		University of Southampton, UK	dat@noc.soton.ac.uk
H. Henry Teng		Nanjing University/George Washington University, USA	hteng@gwu.edu
Masako Tominaga	**	Dept. of Geology and Geophysics - WHOI, USA	mtominaga@whoi.edu
Reinier Van Noort	**	HPT-Laboratory, Utrecht University, The Netherlands	vannoort@geo.uu.nl
A. Joshua West	**	University of Southern California Earth Sciences, USA	joshwest@usc.edu
Anthony Williams-Jones		McGill University, Canada	anthony.williams-jones@mcgill.ca
Liang Zhao		School of Earth Sciences and Engineering, Nanjing University, P. R. China	zhaoliang@nju.edu.cn

Note: *PhD student, **Post-doc and young scientist